Comparison of Human Impact Response in Restraint Systems With and Without a Negative G Strap

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A test program to assess the influence of a negative G strap on restraint dynamics and human impact response was conducted at AFAMRL. There were 131 experimental-level impact tests with volunteer subjects performed in eight different test conditions. Forward-facing ($-G_x$) impacts were carried out on a horizontal accelerator, while vertical ($+G_z$) impact tests were done on a vertical drop tower facility. In both axes, the experimental exposure was an approximate half-sine waveform with peak acceleration up to 10 G and velocity change up to 9.2 m·s^{-1}. Subjects were restrained to the test vehicle using either the PCU-15/P torso harness and lap belt, which is used operationally in such aircraft as the A-20 and F-15, or a conventional double shoulder strap and lap belt configuration. In one half of the test conditions, fixed-length negative G straps were incorporated into these restraint systems. In the other test conditions, the unmodified restraint systems were evaluated. Adding the negative G strap to either restraint system had clearly beneficial effects. These included decreasing the tendency toward submarining in forward-facing impacts, providing better occupant-seat coupling during free falls, and improving vertical impact protection. Sufficient benefits appear to result from use of the negative G strap to warrant a recommendation for its incorporation into selected USAF restraint systems, such as the PCU-15/P torso harness and lap belt. Additional data analysis revealed that the conventional double shoulder strap and lap belt restraint provided better forward-facing and vertical impact protection than the PCU-15/P torso harness and lap belt configuration. Further research at AFAMRL is planned to identify restraint harness features which may improve the performance of current and future impact protection systems.

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ONE INTENDED PURPOSE of a negative G strap is to prevent "submarining" or movement of the torso under the lap belt during forward-facing ($-G_x$) impact accelerations. By tethering the lap belt to the forward portion of the seat, the negative G or crotch strap prevents the lap belt from riding up and over the anterior superior iliac spines, pressing against the abdomen and causing serious internal injury. At the Air Force Aerospace Medical Research Laboratory (AFAMRL), complete transection of the rectus abdominus muscles and hepatic laceration have occurred in anesthetized baboon subjects as the result of submarining during high-acceleration $-G_x$ impacts (unpublished data). In the operational setting, such accelerations experienced by aircrew members during aircraft crashes or during the aerodynamic deceleration immediately following emergency ejections may produce similar injury patterns.

The usefulness of crotch straps as anti-submarining devices was recognized by Stapp (21), who conducted $-G_x$ impact experiments with human subjects restrained by harness configurations with and without antisubmarining straps. The high-acceleration tests in that study most frequently cited used two crotch straps, each attached to an adjacent rear corner of the seat and to the lap belt buckle to form an inverted-V. When these straps were not incorporated into the restraint harness, submarining was noted in some cases. Stapp reported that "the forward motion of the shoulders during impact applies traction to the shoulder straps, raising the lap belt, permitting the lower half of the body to begin bending around it. The upper edge of the belt lodges against the lower margins of the ribs and against the upper abdomen."

The second purpose of a negative G strap is to

provide better mechanical coupling between the seat and its occupant during low-frequency flight vibrations, sustained $-G_z$ acceleration maneuvers, and adverse aircraft motions which may occur if the aircraft departs from controlled flight This function of the tie-down strap is obviously more important than its role as an anti-submarining device since sustained $-G_z$ accelerations causing the aircrew member to become "light" in the seat may be frequently encountered in day-to-day flight operations Inadequate $-G_z$ restraint degrades ability to control the aircraft (1,15,18), causes helmet-canopy contact (14,15), impairs ability to eject in some circumstances (1,18), and predisposes to injury during ejection (5,15,18). Loss of aircraft and death of aircrew members have been attributed to the inadequate $-G_z$ restraint provided by the United States Navy MA-2 integrated torso harness (1) Recently, a USAF RF-4 pilot suffered a cervical vertebral fracture and transient paralysis as a result of $-G_z$-induced helmet-canopy contact and cervical flexion during a subsequent $+G_z$ maneuver (19). The crewmember has a residual neurologic deficit due to this incident

Despite the ancedotal evidence and widespread support among the aeromedical community for use of a negative G strap, an adequate experimental basis for recommending negative G strap incorporation into specific USAF restraint systems was lacking Therefore, AFAMRL in conjunction with the Life Support System Program Office of the Aeronautical Systems Division initiated an investigation of the feasibility and effectiveness of adding a crotch strap to the PCU-15/P torso harness and lap belt, which is used in aircraft equipped with the ACES II ejection seat such as the A-10, F-15, F-16, B-1B, and T-46A. The research effort addressed one aspect of an ACES II restraint modification program undertaken in response to a statement of operational need by the USAF Tactical Air Command for improved restraint during sustained $-G_z$ acceleration, out-of-control flight conditions, and emergency escape

The primary objective of the present study was to evaluate human response to forward-facing ($-G_x$) and vertical ($+G_z$) impacts in operational USAF restraint systems with and without a negative G strap Secondary objectives included comparing human impact response in the PCU-15/P torso harness and lap belt arrangement to such response in a conventional double shoulder strap and lap belt configuration and establishing performance baseline data for use in guiding the development of new and improved restraint systems for advanced tactical fighter aircraft

METHODS

A controlled impact experiment using volunteer subjects was designed to meet these objectives The test conditions investigated are summarized in Table I Testing was accomplished in two phases First, test conditions A, B, C, and D were completed on the AFAMRL Horizontal Impulse Accelerator (HIA) Then, test conditions E, F, G, and H were performed on the AFAMRL Vertical Deceleration Tower (VDT) Experimental exposures of subjects during each phase of testing were randomized

Parametric analysis of matched test conditions permitted the identification of response differences resulting from a single controlled variable, such as negative G strap or restraint harness configuration Eight separate comparisons among the test conditions were performed These were grouped into four comparison sets (Table II) in order to simplify the presentation and discussion of test results.

The volunteer subjects (20 men, 1 woman) were active-duty officers and enlisted personnel at Wright-Patterson Air Force Base. Prior to participation, subjects were required to meet stature, weight, and sitting height criteria for USAF pilots and to complete a medical screening more rigorous than the USAF Flying Class II evaluation (6) The selection method, therefore, was designed to yield a subject sample comparable to the USAF flying population in terms of age and anthropometry, but supranormal in terms of susceptibility to impact injury Characteristics of the subject sample (means and standard deviations) are summarized as follows: age, 25.9 ± 3 9 years; weight, 76.2 ± 9 8 kg; height 175 ± 7.2 cm, sitting height, 92.7 ± 3.4 cm

To minimize the potential for injury to subjects, the tests were conducted at presumed subinjury impact acceleration levels. In order to familiarize subjects with the test procedures and equipment, orientation impacts were performed prior to experimental-level exposures. For the forward-facing or horizontal test phase, 6-G peak (6 7 m · s^{-1}) and 8-G peak (7.9 m · s^{-1}) impact levels were chosen for subject orientation, and the experimental exposure level was 10-G peak (9.1 m · s^{-1}) For the vertical test phase, the orientation exposure was 8-G peak (7.0 m · s^{-1}) and the experimental exposures were performed at 10-G peak (7.9 m · s^{-1}). All acceleration profiles were approximate half-sine waveforms. The applied forces at the higher test levels were generally sufficient to overcome the forces of voluntary muscle contraction and, therefore, produced

TABLE I EXPERIMENTAL CONDITIONS

TEST CONDITION DESIGNATION	A	B	C	D	E	F	G	H
TEST PHASE	Horizontal	Horizontal	Horizontal	Horizontal	Vertical	Vertical	Vertical	Vertical
RESTRAINT SYSTEM	PCU-15/P	PCU-15/P	Conventional	Conventional	PCU-15/P	PCU-15/P	Conventional	Conventional
NEGATIVE G STRAP	Absent	Present	Absent	Present	Absent	Present	Absent	Present

Horizontal ($-G_x$) impacts were conducted on AFAMRL Impulse Accelerator
Vertical ($+G_z$) impacts were performed on AFAMRL Vertical Deceleration Tower

TABLE II COMPARISONS OF MATCHED TEST CONDITIONS

NEGATIVE G STRAP EFFECTS

	Without	vs	With
Horizontal ($-G_x$) Tests	A	(n = 14)	B
	C	(n = 18)	D
Vertical ($+G_z$) Tests	E	(n = 16)	F
	G	(n = 15)	H

RESTRAINT HARNESS EFFECTS

	PCU-15/P	vs	Conventional
Horizontal ($-G_x$) Tests	A	(n = 15)	C
	B	(n = 14)	D
Vertical ($+G_z$) Tests	E	(n = 14)	G
	F	(n = 16)	H

n = number of matched pairs (same subjects tested in both experimental conditions)

a subject response suitable for comparative parametric analysis

The accelerator facility used for the horizontal test phase was the AFAMRL HIA (20) which operates on the principle of differential gas pressure In order to maintain constant impact test conditions, the pretest chamber pressures of the HIA actuator were identical for all experimental-level exposures The AFAMRL VDT was used to perform the impacts in the vertical test phase The impact carriage of this facility moved along vertical rails and supported the test fixture, seat, and restraint system The carriage was elevated to a drop height of 3.35 m and allowed to free fall onto a hydraulic decelerator to produce the desired acceleration profile The carriage drop height, the mass of the test fixture, and the impact plunger were the same for all vertical tests to assure nearly identical impact conditions from test to test

The PCU-15/P torso/parachute harness (formerly known as the PCU-2/P) was used by most male subjects during both phases of the test program (Fig. 1). The smaller male subjects and the female subject used the smaller size but otherwise identical PCU-16/P torso harness. The shoulder straps, attached to the parachute riser and restraint fittings (Koch Part No 015-12231-3) of the PCU-15/P harness, consisted of 4.5-cm wide type I polyester webbing (MIL-W-25361) The lap belt used with the PCU-15/P torso harness was an HBU configuration consisting of 4.5-cm wide type III polyester webbing

The second harness, used as a control or standard of comparison, was a conventional USAF double shoulder strap and lap belt configuration (Fig. 2) The shoulder

Fig. 1. PCU-15/P torso harness and lap belt configuration used in test conditions A and E.

Fig. 2. Conventional double shoulder strap and lap belt configuration used in test conditions C and G.

straps of this restraint were an adjustable type MB-6 harness constructed of 4.5-cm wide type I polyester webbing, and the lap belt was an HBU configuration constructed of 4.5-cm wide type XIII nylon webbing (MIL-W-4088H) The lap belt of each harness was anchored at two locations, while the shoulder straps were anchored at a single location on the aft bulkhead of the test fixture.

The negative G strap (USAF Part No 45402-0101649-01), added to the restraint harnesses in some test conditions (Fig. 3 and 4), consisted of 4 5-cm wide type I polyester webbing In order to accommodate the added negative G strap, a modified type MA-1 harness buckle was used with each lap belt during all tests in the series The crotch strap was anchored at a point 38.1 cm forward of the seat reference axis This position corresponds to the distance from the seat reference axis to the center of the forward edge of the ACES II survival kit lid and is consistent with accepted guidance (4)

The length of the negative G strap used was selected in a static evaluation of several straps of different lengths Subjects representative of the range of subject anthropometry in this study participated in the static evaluation The negative G strap chosen in each test phase best fulfilled the intended purpose of the strap, i e , tethering the lap belt to the forward portion of the seat. For the horizontal tests, the negative G strap was 25.4 cm in length; for the vertical tests, the negative G strap was 21 9 cm in length. The difference in these lengths was because the seat pan was inclined 6° from horizontal during the forward-facing test phase, but it was not inclined during the vertical test phase

Each subject was properly fitted with the PCU-15/P (or PCU-16/P) torso/parachute harness. In particular, the leg straps were adjusted in accordance with the harness technical order so that, when snug, the subject could not assume the fully upright standing position After the subject was seated on the test fixture, the lap belt and shoulder straps were pretensioned to 89 ± 22 N, measured by load cells at the three attachment fittings The tension of the fixed-length negative G strap could not be adjusted Subjects were instructed to assume identical preimpact body positions prior to each test in the series, with head against the headrest while maintaining a mild-to-moderate amount of posterior cervical muscle tension and with arms resting on anterior thighs Subjects wore HGU-26/P flight helmets during the vertical tests, but not during the forward-facing tests to reduce the likelihood of cervical muscle strain

The test fixtures, restraint harnesses, and subjects were instrumented to obtain pertinent data during each experiment. Measured parameters included

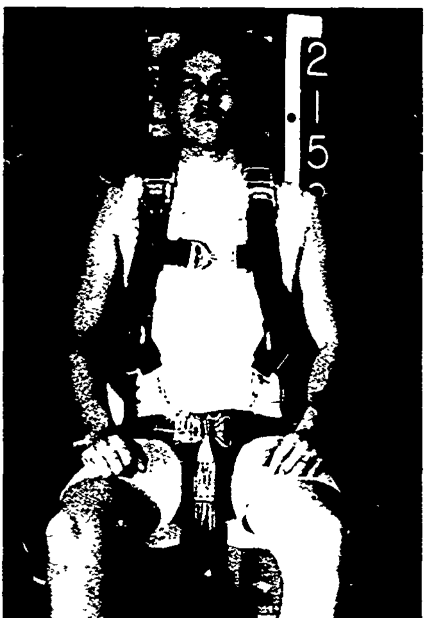

Fig. 3. PCU-15/P torso harness and lap belt configuration with an added negative G strap used in test conditions B and F.

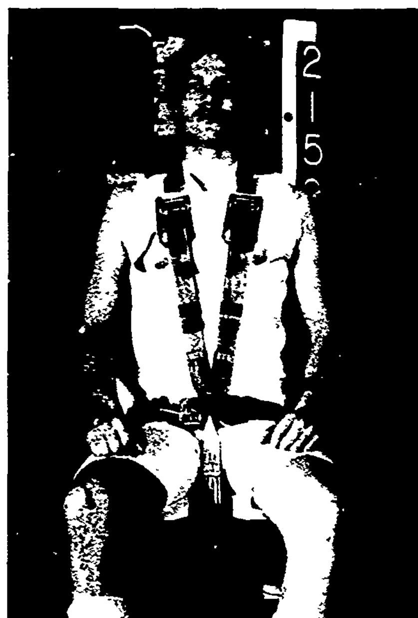

Fig. 4. Conventional double shoulder strap and lap belt configuration with an added negative G strap used in test conditions D and H

acceleration of the test vehicle and seat, velocity of the test platform, seat loads, and loads measured at the restraint harness attachment points Accelerations at the head and chest of the subjects were measured by triaxial translational accelerometers Photogrammetric data were obtained by two high-speed motion picture cameras mounted on the test fixture, permitting measurement of body segment displacements during the impact The left-handed coordinate reference system for acceleration (+X anterior, +Z cephalad) was used during data analysis.

Electronic and photogrammetric data were processed by computer. The Wilcoxon paired-replicate rank test (23) was selected to compare the peak values of measured parameters and to establish the statistical significance of observed trends in the data This analytical approach established each subject as his own control and thereby reduced the effects of biological variability among subjects The 95% confidence level, assuming a two-tailed test, was chosen as the level of statistical significance for analysis of the electronic data. The more liberal 90% confidence level was selected for rejection of the null hypothesis in the photogrammetric data analysis due to the greater variance in these data compared to the electronic data

EVALUATION CRITERIA

The evaluation criteria for this study were based on the fundamental principles of biomechanical protection In general, injuries resulting from impact accelerations are due to differential acceleration of body segments or parts and excessive internal structural loading. In particular, human tolerance to $+G_z$ impacts appears to be limited by vertebral compression fracture Therefore, it is most important during vertical impact to minimize resultant seat load since this load indirectly reflects axial loading of the vertebral column Of secondary importance during vertical impact is that head and chest accelerations be minimized because the accelerative forces acting on these body segments may produce bending and, therefore, reduce the load-carrying capability of the vertebral column

During the vertical free fall preceding impact on the drop tower facility, a near zero-G environment is established, causing the subject to become "light" in the seat Resultant seat load was used during this period as an indicator of the degree of man-seat coupling We assumed that the higher the seat load the better the man-seat coupling during free fall. Thus, resultant free-fall and impact seat loads and resultant head and chest accelerations were considered critical response parameters during the vertical test phase.

The mechanism of injury limiting human tolerance to $-G_x$ impacts is less clear. Medical adverse effects include cardiovascular, neurologic, and musculoskeletal consequences Relative bradycardia has been reported following 15-G peak, 6 1 m·s^{-1} impacts (17). This effect was believed to be vagal-mediated since it could be blocked by the pre-impact administration of the atropine (22). Intraventricular conduction defects in the form of bundle branch blocks have been noted following forward-facing impacts at 11 3-G peak, 14 2 m·s^{-1} (13). These isolated cardiac conduction disturbances were transient in nature and required no treatment Signs and symptoms of cardiovascular shock have been noted following $-G_x$ impacts exceeding 30-G peak with onset rates of 1,000 G·s^{-1} or greater (21) The involved subjects were temporarily incapacitated, but vital signs rapidly improved with recumbency

Temporarily incapacitating neurologic disturbances have been observed following experimental and operational forward-facing impacts Transient visual disturbances have been reported after $-G_x$ impacts above 35 G by Stapp (21) and Beeding (2) Reader (16) has noted anecdotal reports of inappropriate crewmember behavior resulting from presumed concussion during aircraft crashes and ditchings However, such behavioral disturbances in a laboratory setting presumably would be transient and reversible Musculoskeletal trauma, in the form of vertebral compression fractures, has also been observed after $-G_x$ human impact experiments One fracture occurred at a peak acceleration below 20 G but with a relatively high velocity change of 17 4 m·s^{-1} (12). Other vertebral fractures have been observed at peak accelerations in excess of 30 G with onset rates over 1,000 G·s^{-1} (2). Although no neurologic sequelae have been reported as a result of such fractures, the injuries nevertheless carry the potential for prolonged disability due to chronic back pain or for permanent neurologic damage

In light of these considerations, vertebral compression fracture may limit $-G_x$ impact tolerance as well as $+G_z$ tolerance, in spite of the cardiovascular and neurologic effects observed at lower peak acceleration levels Thus, during forward-facing impact tests, minimizing seat loads, which are generally reflective of vertebral loading, appears to be warranted However, probably equal in importance is the goal of minimizing body segment accelerations, particularly head accelerations, in view of the transient but potentially incapacitating neurologic consequences of excessive head acceleration during $-G_x$ impacts

Also, for the purposes of this study, the tendency toward torso submarining during forward-facing impact was estimated by measuring displacement of a target fixed to the subject's knee A side view of the impact response (photogrammetric data) was used to quantify knee displacement from the seat reference axis Relatively large knee displacement was assumed to indicate a greater tendency toward submarining and thus a reduction in knee displacement was considered to be a favorable finding In summary, the critical response parameters in the horizontal test phase were seat loads, resultant head and chest accelerations, and resultant knee displacement

RESULTS

Selected response parameters from each set of Wilcoxon comparisons are summarized in Tables III–VI Means, standard deviations, and percentage increase in parameter means are presented for the peak values of these parameters. In these tables, an asterisk designates a statistically significant difference in a response parameter at the chosen confidence level

Means and standard deviations of all measured and computed response parameters in these test conditions have been presented elsewhere (9)

For the 67 tests conducted during the horizontal test phase, the mean peak sled acceleration was 9 48 ± 0.08 G with a velocity change of 9.20 ± 0.06 m·s^{-1} For the 64 experimental-level tests conducted during the vertical test phase, the mean peak carriage acceleration was 9.96 ± 0 06 G, and the velocity change was 8 00 ± 0.05 m·s^{-1}. The impact test conditions during both phases of the experiment, therefore, were well controlled

Horizontal Test Phase

Negative G strap effects are presented in Table III. In Wilcoxon comparison A-B, the effects of incorporating a negative G strap into the PCU-15/P torso harness and lap belt configuration are examined No statistically significant differences were found in vertical seat load or resultant head or chest accelerations However, resultant knee displacement was significantly increased by an average of 11% when the negative G strap was not used in the PCU-15/P configuration Therefore, addition of the crotch strap to this restraint system provides more effective pelvic restraint and decreases the tendency toward torso submarining during forward-facing impact.

In Wilcoxon comparison C-D, the influence of the negative G strap on $-G_x$ response in the conventional restraint was assessed Findings among the critical response parameters in this comparison were similar to the findings in comparison A-B No statistically significant changes in resultant head or chest accelerations were observed. Resultant knee displacement was, again, significantly higher without the crotch strap, this time by an average of 20%. We, therefore, concluded that addition of the negative G strap decreased the tendency toward submarining. In this comparison, vertical seat load was significantly increased in the condition with the added negative G strap by an average of 14% While this could indicate that greater vertebral column loading may be anticipated when subjects are exposed to $-G_x$ impacts in a conventional harness with an added negative G strap, a portion of the increased seat load may represent vertical components of negative G strap and lap belt tensions acting through the pelvis to the seat. The relative contributions of these two potential effects is impossible to determine from the available data However, the second effect is believed to predominate purely from geometric considerations

Changes in restraint dynamics due to crotch strap incorporation were also evaluated The total shoulder strap load was significantly increased when the negative

TABLE III HORIZONTAL TEST PHASE NEGATIVE G STRAP EFFECTS

RESPONSE PARAMETER	PCU-15/P CELL A WITHOUT	PCU-15/P CELL B WITH	% ↓	CONVENTIONAL CELL C WITHOUT	CONVENTIONAL CELL D WITH	% ↓
	(n = 14)			(n = 18)		
Resultant Head Acceleration (G)	17 4 ±4 4	16 8 ±4 4	4	16 7 ±3 6	17 8 ±5 4	7
Resultant Chest Acceleration (G)	24 6 ±4 5	25 5 ±5 2	4	16 1 ±2 2	17 3 ±2 1	7
Total Shoulder Strap Load (N)	2930 ±440	3080 ±398	5*	2760 ±449	3240 ±556	17*
Time to First Peak Shoulder Strap Load (ms)	83 ±5	85 ±4	2	72 ±14	77 ±4	7*
Total Lap Belt Load (N)	8580 ±1230	9260 ±1610	8*	7530 ±911	8250 ±1240	10*
Time to Peak Lap Belt Load (ms)	72 ±4	74 ±4	3*	70 ±4	70 ±3	0
Vertical Seat Load (N)	6690 ±1040	6810 ±1290	2	5940 ±892	6800 ±1350	14*
	(n = 10)			(n = 15)		
Resultant Knee Displacement (cm)	24 8 ±3 5	22 4 ± 3 4	11**	23 7 ±5 3	19 7 ±4 1	20**

Data presented are means ± S D for maximum accelerations, loads and displacements and for time to maximum strap loads
*Means are statistically different by the Wilcoxon paired-replicate rank test ($2\alpha \leq 0\ 05$)
**Means are statistically different by the Wilcoxon paired-replicate rank test ($2\alpha \leq 0\ 1$)
n = number of matched pairs Value of n is different for photogrammetric data due to partial data loss

G strap was added to either restraint configuration. The percentage increase in this load was larger for the conventional harness than for the PCU-15/P configuration. These findings may have been anticipated on the basis of geometric considerations. Addition of the negative G strap to the conventional configuration establishes a direct load path from the shoulder straps to the seat, thereby improving the load-carrying capability of the shoulder straps. In the PCU-15/P configuration, on the other hand, there is no direct physical connection between the added negative G strap and the torso harness. Nevertheless, the total shoulder strap load was still significantly higher with the added crotch strap than without it, probably due to the more effective pelvic restraint provided by the crotch strap accompanied by an increased forward inertial response of the upper torso.

The time to peak shoulder strap load was not significantly changed when the negative G strap was added to the PCU-15/P configuration. However, the time to peak shoulder strap load was significantly delayed by an average of 5 ms when the negative G strap was added to the conventional double shoulder strap and lap belt configuration. Though the latter finding may have been anticipated because of the direct physical connection between the torso harness and the negative G strap, the reason for the increased lag appears to be more complex. The time history of the shoulder strap load in the conventional harness was biphasic; i.e., it had two peaks. The amplitude of the first peak was higher in 12 of the 18 tests when the negative G strap was not used (test condition C). However, it was consistently higher when the negative G strap was used in test condition D. Therefore, incorporating a negative G strap into the conventional restraint appeared to increase the amplitude of the total shoulder strap load and the time required for that load to reach its peak value.

The total lap belt load was also significantly increased when the crotch strap was used in either restraint configuration. These increases may be attributed to the associated increases in shoulder strap loads in test conditions B and D.

The differences between the two restraint systems observed in the forward-facing tests are presented in Table IV. In Wilcoxon comparison A-C, the two restraint systems without added negative G straps were

TABLE IV. HORIZONTAL TEST PHASE: RESTRAINT CONFIGURATION EFFECTS

RESPONSE PARAMETER	WITHOUT CROTCH STRAP: CELL A PCU-15/P	CELL C CONV	%↑	WITH CROTCH STRAP: CELL B PCU-15/P	CELL D CONV	%↑
	(n = 15)			(n = 14)		
Resultant Head Acceleration (G)	17.0 ±3.7	16.7 ±3.5	2	16.3 ±4.1	18.2 ±5.6	12
Resultant Chest Acceleration (G)	24.5 ±5.1	16.2 ±2.4	51*	26.2 ±5.1	17.3 ±2.0	51*
Total Shoulder Strap Load (N)	2990 ±530	2700 ±404	11*	3120 ±420	3140 ±439	<1
Time to First Peak Shoulder Strap Load (ms)	85 ±[illegible]	73 ±16	16*	85 ±4	77 ±5	10*
Total Lap Belt Load (N)	8540 ±1260	7530 ±790	13*	9310 ±1590	8300 ±1290	12*
Time to Peak Lap Belt Load (ms)	72 ±4	70 ±4	3	74 ±4	69 ±3	7*
Negative G Strap Load (N)				604 ±229	945 ±359	56*
Time to Peak Negative G Strap Load (ms)				243 ±26	117 ±37	108*
Vertical Seat Load (N)	6590 ±1060	5940 ± 876	11*	6790 ±1290	6740 ±1350	<1
	(n = 11)			(n = 12)		
Resultant Knee Displacement (cm)	24.8 ±6.0	24.0 ± 5.3	3	23.4 ±3.3	20.6 ±2.9	14**

Data presented are means ± S.D. for maximum accelerations, loads, and displacements and for time to maximum strap loads.
*Means are statistically different by the Wilcoxon paired-replicate rank test (2 α ≤0.05).
**Means are statistically different by the Wilcoxon paired-replicate rank test (2 α ≤0.1).
n = number of matched pairs. Value of n is different for photogrammetric data due to partial data loss.

compared. Vertical seat load was 11% higher for the PCU-15/P configuration than for the conventional configuration. This finding may be related to increased lap belt loads rather than increased spinal loads. Also, the resultant chest acceleration was 51% higher for the PCU-15/P configuration. However, no statistically significant difference was observed in resultant head acceleration nor was there a significant change in resultant knee displacement. The latter finding suggests there is no difference in anti-submarining performance between the two restraint configurations Nevertheless, we concluded that the PCU-15/P configuration is inferior to the conventional harness by virtue of the chest acceleration and seat load findings The significantly lower chest acceleration measured in the conventional configuration indicates superior coupling of the upper torso to the seat structure by the two shoulder straps which are directly linked to the lap belt in that configuration.

In comparison B-D, the two restraint configurations with added negative G straps were compared No statistically significant difference was observed in vertical seat load or resultant head acceleration However, resultant chest acceleration was significantly higher in the PCU-15/P configuration than in the conventional configuration. In addition, resultant knee displacement was significantly larger in the PCU-15/P configuration, suggesting a greater tendency toward torso submarining In summary, analysis of the critical response parameters in comparisons A-C and B-D revealed that the PCU-15/P configuration provided less adequate forward-facing impact protection than the conventional configuration, whether or not the negative G strap was used.

Analysis of the strap loads and times to peak strap load provided additional supporting evidence for this conclusion Total shoulder strap load was significantly higher in the PCU-15/P configuration compared to the conventional configuration when the negative G strap was not used in either restraint system (comparison A-C) However, when the negative G strap was added to both configurations (comparison B-D), no significant difference was observed in the total shoulder strap load This is probably due to the large increase in shoulder strap load associated with adding the negative G strap to the conventional configuration since a direct load path is established from the shoulder straps to the seat via the negative G strap In addition, time to peak shoulder strap load was significantly greater for the PCU-15/P configuration whether or not the negative G strap was used These findings are consistent with the interpretation that the PCU-15/P configuration permits greater displacement of the upper torso from the seat before the subject is effectively restrained

In both comparisons, the maximum lap belt load was significantly higher and occurred slightly later in the PCU-15/P configuration than the conventional configurations These findings also indicate the relatively poor performance of the PCU-15/P configuration

Finally, in comparison B-D, the maximum negative G strap load was 56% higher in the conventional configuration than in the PCU-15/P configuration This finding was expected since a portion of the shoulder strap load was carried via the negative G strap to the seat structure Also, the peak negative G strap load occurred 108% later in the PCU-15/P configuration compared to the conventional configuration. This longer delay until peak tension in the negative G strap is consistent with the interpretation that the PCU-15/P configuration permitted more movement of the pelvis during impact than the conventional configuration. This finding is also in keeping with the greater resultant knee displacement seen in the former condition.

Vertical Test Phase

The negative G strap effects observed in the vertical test phase are summarized in Table V Results of adding a negative G strap to the lab belt used with the PCU-15/P torso harness were obtained in Wilcoxon comparison E-F Resultant free-fall seat load was significantly higher when the crotch strap was used, indicating better man-seat coupling during the free-fall phase of the experiment In addition, resultant impact seat load was significantly lower with the added negative G strap, suggesting less vertebral column loading of the subjects during impact Resultant head and chest accelerations were not significantly different in the two test conditions On the basis of these data, we concluded that incorporation of the negative G strap improved the vertical impact protection performance of the PCU-15/P torso harness and lap belt configuration

In comparison G-H, the effect of adding a negative G strap to the conventional configuration was assessed. Similar findings among the critical response parameters were seen in this comparison insofar as resultant free-fall seat load was increased and resultant impact seat load was decreased when the negative G strap was used However, the magnitudes of the changes in these parameters were significantly greater in this comparison, indicating that the negative G strap had an even greater beneficial effect when added to the conventional configuration compared to the PCU-15/P configuration This conclusion was also supported by the findings that resultant head and chest accelerations were significantly less when the negative G strap was added to the conventional configuration. In summary, analysis of the critical response parameters in these two comparisons revealed that adding the crotch strap to either restraint system improved man-seat coupling during free fall as well as the vertical impact protection performance of the restraint system.

Restraint dynamics were elucidated by further study of the available data in these two comparisons. In comparison G-H, addition of the negative G strap dramatically reduced the total shoulder strap load at impact This reduction was believed to be due to better mechanical coupling of the upper torso with the seat structure during free fall of the impact carriage by virtue of the direct load path from the shoulder strap tie-down point to the negative G strap tie-down point in this configuration On the other hand, when the crotch strap was added to the PCU-15/P configuration (comparison E-F), the total shoulder strap load was not significantly changed This finding is consistent with the fact there is

TABLE V. VERTICAL TEST PHASE NEGATIVE G STRAP EFFECTS

	PCU-15/P			CONVENTIONAL		
RESPONSE PARAMETER	CELL F WITHOUT	CELL F WITH	% ↓	CELL G WITHOUT	CELL H WITH	% ↓
	(n = 15)			(n = 15)		
Resultant Head Acceleration (G)	13.3 ±1.2	13.[illegible] ±0.8	2	12.8 ±0.9	12.0 ±0.9	7*
Resultant Chest Acceleration (G)	19.8 ±2.1	[illegible] ±[illegible]2	3	16.5 ±1.2	15.2 ±1.0	9*
Total Shoulder Strap Load (N)	479 ±132	464 ±130	3	327 ±166	168 ±203	95*
Time to Peak Shoulder Strap Load (ms)	80 ±11	79 ±1[illegible]	1	81 ±10	97 ±12	20*
Total Lap Belt Load (N)	4[illegible] ±18[illegible]	394 ±122	25*	559 ±177	378 ±106	48*
Time to Peak Lap Belt Load (ms)	68 ±6	70 ±14	3	73 ±13	74 ±14	1
Resultant Free-Fall Seat Load (N)	11[illegible]0 ±220	1240 ± 306	13*	1210 ±363	1820 ±478	50*
Resultant Impact Seat Load (N)	9980 ±10[illegible]0	85[illegible]0 ± 1100	3*	8400 ±987	7900 ±1050	6*

Data presented are means ± S.D. for maximum accelerations, loads, and for time to maximum strap loads
*Means are statistically different by the Wilcoxon paired-replicate rank test ($2\alpha \leq 0.05$)
n = number of matched pairs.

no direct connection between the shoulder straps of the PCU-15/P torso harness and the lap belt with an added negative G strap.

The time from the start of impact to maximum shoulder strap load was increased significantly when the negative G strap was added to the conventional configuration (comparison G-H). This time shift appears to be due to the phase relationship between the negative G strap loads and the shoulder strap loads rather than to a change in the stiffness of the restraint configuration

In both comparisons, the lap belt loads were significantly higher without the negative G strap. These findings are consistent with the fact that the negative G strap shares the loads required to restrain the pelvis, which are generally carried by the lap belt.

Differences between the two restraint systems in the vertical test phase are shown in Table VI. In Wilcoxon comparison E-G, the resultant chest acceleration and total shoulder strap load were significantly reduced in the conventional configuration compared to the PCU-15/P configuration. No significant change was observed in resultant head acceleration. Finally, the resultant free-fall seat load was significantly increased while the resultant impact seat load was significantly decreased in the conventional configuration compared to the PCU-15/P configuration. These findings are consistent with the interpretation that the PCU-15/P configuration provides relatively poor man-seat coupling during free fall and less adequate vertical impact protection than the conventional restraint.

Vertical impact response differences in the two restraint systems with added crotch straps were assessed in comparison F-H. Based on similar findings among the critical response parameters, we drew the same conclusions as in comparison E-G. Resultant free-fall seat load was significantly greater and resultant impact seat load was significantly less in the conventional configuration. In addition, resultant head and chest accelerations were significantly less in the conventional configuration compared to the PCU-15/P configuration. Finally, the dramatic differences in shoulder strap load and negative G strap load seen in comparison F-H demonstrate the effectiveness of the direct load path from shoulder straps to seat via the crotch strap in test condition H. The maximum tension in the negative G strap was significantly greater and the maximum load at the shoulder strap anchor point was significantly less in the conventional configuration compared to the PCU-15/P configuration

DISCUSSION

These tests demonstrated that negative G strap incorporation into the PCU-15/P configuration or the conventional configuration reduced the tendency toward torso submarining during forward-facing impact, improved occupant-seat coupling during free fall, and improved vertical impact protection. During the forward-facing

TABLE VI VERTICAL TEST PHASE RESTRAINT CONFIGURATION EFFECTS

	WITHOUT CROTCH STRAP			WITH CROTCH STRAP		
RESPONSE PARAMETER	CELL E PCU-15/P	CELL G CONV	% ↕	CELL F PCU-15/P	CELL H CONV	% ↕
	(n = 14)			(n = 16)		
Resultant Head Acceleration (G)	13 3 ±1 3	12 8 ±0 9	4	12 9 ±0 9	12 1 ±0 9	7*
Resultant Chest Acceleration (G)	19 9 ±2 1	16 6 ±1 9	20*	19 1 ±2 5	15 4 ±1 2	24*
Total Shoulder Strap Load (N)	469 ±139	305 ±147	54*	473 ±143	179 ±202	164*
Time to Peak Shoulder Strap Load (ms)	82 ±16	81 ±10	1	80 ±11	97 ±12	21*
Total Lap Belt Load (N)	517 ±180	554 ±183	7	413 ±119	367 ±112	13
Time to Peak Lap Belt Load (ms)	69 ±5	72 ±12	4	73 ±15	73 ±15	0
Negative G Strap Load (N)				181 ±76	448 ±114	148*
Time to Peak Negative G Strap Load (ms)				137 ±28	129 ±14	6
Resultant Free-Fall Seat Load (N)	1080 ±234	1230 ± 371	14*	1250 ±325	1830 ±465	46*
Resultant Impact Seat Load (N)	9130 ±1110	8400 ± 1020	9*	8700 ±1180	7850 ±1040	11*

Data presented are means ± S D for maximum accelerations, loads, and for time to maximum strap loads
*Means are statistically different by the Wilcoxon paired-replicate rank test ($2\alpha \leq 0.05$)
n = number of matched pairs

impacts, negative G strap incorporation produced no adverse changes among critical response parameters in the PCU-15/P configuration and only raised the question of possible performance degradation in the conventional configuration No medical contraindications to negative G strap incorporation were found in this study.

In a concurrent study performed on the AFAMRL Dynamic Environment Simulator, negative G strap addition to the PCU-15/P configuration was shown to have a beneficial effect in a sustained $-2.0\ G_z$ environment. Although no statistically significant differences in tracking task performance were found, subject vertical displacement from the seat was significantly less when the negative G strap was used (10) Reduced vertical displacement from the seat during sustained $-G_z$ acceleration has also been observed when a crotch strap was added to the U S Navy MA-2 torso harness (11)

In assessing the utility of negative G or crotch strap incorporation into various restraint systems, it is useful to consider that the negative G strap functions separately in the operational and impact contexts.

In the operational context, the perceived user benefit of negative G strap incorporation is the improved support during $-G_z$ acceleration maneuvers resulting from decreased upward rotation of the lap belt In some restraint configurations, notably the conventional restraint used in this study, the negative G strap links the shoulder straps to the lower seat structure, thereby permitting shoulder strap loads to be carried directly to the seat

In the impact context, the primary perceived benefit of negative G strap incorporation is to decrease the likelihood of torso submarining under the lap belt during $-G_x$ impact acceleration By tethering the lap belt to the lower seat structure, the negative G strap reduces the tendency for the lap belt to rotate up and over the anterior superior iliac spines of the pelvis. During such forward-facing impacts, shoulder strap loads may also be carried to the lower seat structure in a manner similar to the sustained $-G_z$ case, but the origin of the $-G_x$ loading is different and the load magnitude is greatly increased

The perceived risk of negative G strap incorporation is primarily the potential for injury of the groin or genitalia during a $-G_x$ impact associated with ejection or aircraft crash. Avoiding significant submarining in such cases is essential to prevent loading of the anterior abdominal wall by the lap belt and, therefore, the risk of

significant internal injury. A correctly designed restraint does not prevent submarining by the application of direct negative G strap loading of the genitalia or groin Nevertheless, such loading is conceivable, particularly with a loosely adjusted lap belt or an inferior negative G strap attachment located too far aft for the crewmember in question

Limited operational experience with crotch straps has been accrued in foreign military services, notably the United Kingdom, and in the T-38 aircraft previously used as USAF Thunderbirds The most extensive USAF operational experience with a restraint harness which incorporates a negative G strap has been with the harness of the F/FB-111. Although ejection experience in the F/FB-111 has been associated with a relatively high rate of vertebral fracture among survived ejectees, ejection-related injuries do not commonly include lesions of the groin or genitalia (7,8). Only one scrotal laceration and two thigh contusions may be attributed to the presence of the negative G strap in the F/FB-111 restraint system. The crewmember who incurred a 5-cm scrotal laceration also suffered multiple vertebral fractures during a near nose-down landing impact of the crew module resulting from a failure of the parachute suspension system. The ejection data, therefore, suggest that the F/FB-111 crotch strap functions without producing significant injury to the groin or genitalia Furthermore, extensive human impact tests of the F/FB-111 restraint system (with the shoulder strap anchor point slightly modified) in all three cardinal axes have not been associated with clinically significant problems in this region (3)

Nevertheless, we cannot quantitatively predict the operational injury potential associated with negative G strap addition to the PCU-15/P torso harness and lap belt configuration, for example We presume that the greatest likelihood for injury in an open ejection seat is during transient $-G_x$ accelerations resulting from seat deceleration with drogue parachutes or from aircraft crash landing All indications from the relevant operational and experimental data are that operational injuries of the groin or genitalia due to negative G strap incorporation will be unlikely Furthermore, those injuries which do occur are likely to be clinically inconsequential or to be associated with unrelated but more serious injuries in other organ systems. These conclusions are predicated on the consistent proper adjustment and pretensioning of an appropriately designed restraint system

On the basis of the these test results and other available evidence, sufficient benefits appear to derive from use of the negative G or crotch strap to warrant a recommendation for its incorporation into selected USAF restraint systems, notably the PCU-15/P torso harness and lap belt configuration Designs for incorporation should be based on knowledgeable exploitation of potential benefits and avoidance of potential hazards

Finally, the conventional double shoulder strap and lap belt restraint is clearly preferable to the PCU-15/P torso harness and lap belt configuration as a forward-facing or vertical impact protection device, whether or not a negative G strap is used In the conventional configuration, there is better integration of the lap belt and shoulder straps, addition of the negative G strap provides a direct load path by which shoulder strap loads may be carried to the seat structure On the other hand, in the PCU-15/P configuration the lap belt with or without the added negative G strap is not directly attached to the shoulder straps of the torso harness The relatively poor integration among the restraint straps causes the PCU-15/P configuration to be a relatively poor impact protection device. This is not surprising since the system was originally designed to function as a parachute harness Additional research at AFAMRL is in progress to identify restraint harness features which may further improve the performance of current as well as future USAF restraint systems

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